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Upland Soil Erosion Monitoring and Assessment: An Overview

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Upland Soil Erosion Monitoring and Assessment:

An Overview

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Washington, DC

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Abstract

Soil erosion monitoring and assessment are important tools in determining impacts from land management practices. Various methods have been used by the Bureau of Land Management to monitor soil erosion. This technical note is intended to aid resource specialists in evaluating techniques for monitoring and assessing upland soil surface erosion, other than gully erosion. A brief discussion of erosion processes is incorporated in this document. Highlighted monitoring techniques include visual indicators of erosion, watershed cover, remote sensing cover, silt fence catchments, erosion bridge, erosion plots, close-range photogrammetry, and cesium-137. An overview, brief discussion on procedure, advantages and disadvantages, and data analysis considerations are summarized for each monitoring technique. Listed references provide more detailed information about each technique and instructions on implementing erosion monitoring techniques.

Introduction

The Bureau of Land Management (BLM) manages more than 245 million acres of public lands, primarily located in 12 western states including Alaska. The soil, vegetation, climate, and geomorphology across BLM-managed lands vary drastically. For example, the Alaskan tundra has permafrost soils; lichens, mosses, sedges, and dwarfed shrub vegetation; very cold, dry weather with most precipitation falling as snow; and hummocky, nearly level terrain. The conifer rainforests of the Pacific Northwest have well-weathered soils on steep mountain slopes that contrast with the deserts of the Southwest, which have a very dry, hot climate, aridic soils, and sparse shrubby vegetation.

The demand for data that provides reliable measures regarding the health of public land has increased in recent years. Surface condition is often used as a land health indicator and can be used to identify areas that need additional monitoring. Monitoring techniques that measure changes in rates of erosion can be very useful to land managers.

This BLM technical note is intended to aid resource specialists in evaluating and selecting techniques for monitoring and assessing upland soil surface erosion. To apply one of these techniques, refer to the provided reference material for specific procedures. Qualitative monitoring methods provide land managers and resource specialists with cost-effective techniques for determining the present status and indicators of apparent trend for one or more natural resources. Qualitative monitoring methods can be conducted on extensive acreage in a relatively short time and can indicate where resource problems may be occurring. More intensive monitoring methods provide more detailed, quantitative information about the condition and trend of one or more natural resources.

Soil erosion costs the United States between $30 and $44 billion annually (Morgan 2005; Pimental et al. 1995). These costs represent: losses in food and fiber production; replacement of

lost soil nutrients by increased fertilizer use; increased road, dam, and other infrastructure maintenance costs; decreased water storage capacity of the soil, which can result in increased irrigation requirements; repairs from increased flooding; lost recreational opportunities due to reduced water quality, air quality, and wildlife habitat degradation; and erosion prevention measures. Although erosion is an important natural process on public lands, when accelerated by human-induced activities, erosion can have substantial impacts on the productivity and use of that land. Additional impacts from erosion on public lands include loss of wetlands and riparian areas, vegetation community conversion to undesirable states, reduced plant productivity, increased susceptibility to weed invasion, and reduced water and air quality. Erosion monitoring is needed to identify potential problem areas and document erosion rates that are predictive of, or exceed, a critical threshold that could permanently degrade the land or cause serious offsite impacts, such as sedimentation.

Various techniques have been used by the BLM and other land management agencies to monitor surface erosion. Most techniques currently used are site specific and involve a resource specialist visiting the site and observing visual indicators of erosion or making direct measurements of erosion or erosion indicators, such as percent cover. Remote sensing is an emerging technology that can be used to monitor erosion over extensive acreage. Thus, erosion monitoring can be conducted at multiples scales to document the impacts of past management activities and catastrophic natural events, such as wildfire (Corwin et al. 2006). Scale refers to both the spatial and temporal variability in soil erosion.

Soil Erosion Processes and Mitigation

Erosion is the wearing away of the land surface by running water, wind, ice, or other natural or anthropogenic agents that abrade, detach, and remove geologic parent material or soil from one point on the earth's surface and deposit it elsewhere, including such processes as gravitational creep (Soil Science Society of America 2001). Geologic or natural erosion occurs under natural environmental conditions and geologic processes. Accelerated erosion is erosion in excess of natural rates, usually as a result of anthropogenic activities (Soil Science Society of America 2001). Major environmental disturbances, such as wildfire resulting from human changes in the natural fire processes, can also accelerate erosion.

There are many prudent land management practices that will help reduce erosion. Examples of these practices include maintaining adequate plant, litter, and biological soil crust cover to protect a watershed; diminishing soil compaction; maintaining soil aggregate stability (the amount of stable aggregates against flowing water); applying good road building practices; reducing catastrophic wildfire conditions; and managing off-highway vehicle use. Other practices include concurrent reclamation of areas disturbed by mining and energy development, designating skid trails for timber harvest, proper road maintenance, and implementing sound livestock grazing management practices.

Guidance documents outlining these land management practices include each state's rangeland standards and guidelines for livestock grazing management on BLM lands; standards for public land health and guidelines for recreation management on BLM lands for some states (e.g., Utah and Colorado); Grazing Management Processes and Strategies for Riparian-Wetland Areas, TR 1737-20 (Wyman et al. 2006); the Forest Practices Act for each state; Surface Operating Standards and Guidelines for Oil and Gas Exploration and Development (USDI and USDA 2007); and many others.

Accelerated erosion can result in onsite impacts, such as loss of soil productivity, and offsite impacts, such as sedimentation. Water erosion, runoff, and sediment delivery to streams are interrelated. For example, increases in runoff result in increased sheet, rill, and gully erosion, which results in increased sediment delivery to streams. Wind erosion and mass soil movement can also deliver sediment to streams as well as have major impacts on air quality.

Water Erosion

Surface water erosion processes are controlled by the intensity, timing, and duration of rainfall events and the size of raindrops; snowmelt runoff volume and timing; surface soil texture, structure, and organic matter content; soil depth and hydraulic conductivity; soil compaction; slope steepness and length; and watershed cover (Morgan 2005). Total cover is the most important management-related factor affecting water erosion, but plant basal cover and spatial distribution of plants is also important (Herrick et al. 2005). Plant basal cover is resistant to rill and splash erosion. Large gaps in spatial distribution of plants can result in increased runoff and rilling, as well as increased wind speed, which causes greater wind erosion. Arid and semiarid lands in the western United States, which constitute the majority of lands managed by the BLM, are vulnerable to erosion and subsequent degradation because of a combination of factors, such as low vegetation cover, steep slopes, often shallow and rocky soils with low organic matter content, low infiltration rates, and infrequent but high-intensity thunderstorms.

Several models, such as the Water Erosion Prediction Project (WEPP) and the Revised Universal Soil Loss Equation (RUSLE), are available for predicting water erosion rates on rangeland and forest ecosystems. WEPP is a process-based, continuous simulation erosion prediction model that is applicable to hillslope erosion processes and simulation of the hydrologic and erosion processes on small watersheds. Various interfaces have been developed for WEPP, including several U.S. Forest Service-derived interfaces, such as Disturbed WEPP, WEPP Road, Erosion Risk Management Tool (ERMiT), Fuel Management Erosion Analysis (FuME), and a geospatial interface, GeoWEPP. WEPP interfaces have been extensively used for calculating rill and interill erosion on forest and rangeland ecosystems. Improvements to the WEPP model are being developed for rangeland use by the Agricultural Research Service (Spaeth et al. 2006; Wei et al. 2008). RUSLE is an erosion prediction model that was developed as an improvement on the empirical model USLE. It was originally developed to determine impacts of agricultural practices on erosion but has been adapted for application on forests and rangeland. RUSLE has some application limitations for some uses, such as postfire erosion prediction, since it only calculates average annual erosion.

Upland water erosion occurs on land that is upslope from any stream channels, rivers, lakes, or other water bodies. It can be classified by the type of erosion that occurs.

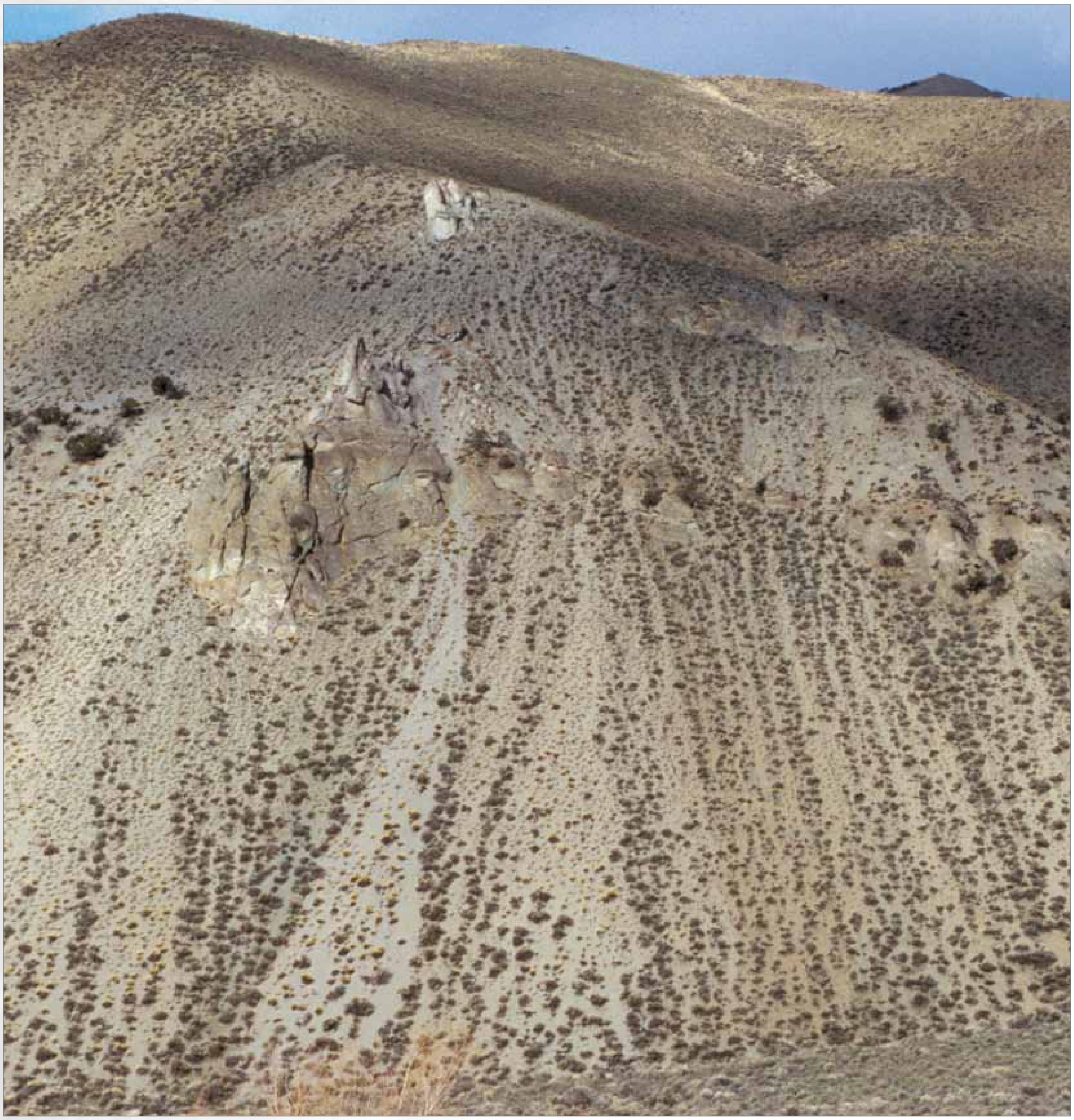
- Sheet, splash, or interill erosion is the removal of a fairly uniform layer of soil from the land surface by raindrop splash or runoff water.
- Rill erosion happens as a result of concentrated overland flow that creates small channels up to a few inches in depth. The width and spacing of these channels will depend on soil properties (e.g., texture and structure) and management practices (e.g., tillage, roads, or trails).
- Gully erosion creates, in a comparatively short time period, relatively narrow channels that can be 1–2 feet to as much as 75–100 feet in depth (Harvey et al. 1985). Severe gully erosion can, to a considerable extent, limit most uses on an effected hillslope. There are no universal and only a few local predictive models available for gully erosion. Gully erosion is very sensitive to increases in runoff and concentration of water flow across the landscape. Beyond reference to Technical Reference 1734-6 (Pellant et al. 2005), techniques for assessing or monitoring gully erosion are not discussed in this technical note.

Wind Erosion

Wind erosion occurs when wind speed exceeds the critical threshold; thus, surface soil particles are no longer held in place. Wind velocity at the soil surface varies greatly depending on wind patterns in a particular area and obstructions to wind created by uneven landform surfaces, plants, and other obstructions. Snow cover and high surface soil moisture reduce vulnerability of soil to wind erosion.

Soil texture, organic matter content, calcium carbonate reaction, and size and durability of soil surface aggregates largely determine the susceptibility of soil to wind erosion (Soil Survey Staff 1996). The poorly aggregated medium and finer sand soils are the most susceptible to wind erosion, and well-aggregated silty clay loams and silts are the least susceptible to soil blowing. Soil particles larger than 1 millimeter can roll on the ground during high wind storms; particles between 0.1 and 1 millimeter will bounce along the ground; and particles less than 0.1 millimeter can become airborne and travel long distances. Airborne particles can result in air quality problems, such as reduced visibility and increases in PM_{10} or $PM_{2.5}$ particulates in the air. Airborne particulate matter that is 10 microns and smaller, and especially 2.5 microns and smaller, can get into the lungs and cause respiratory ailments in humans.

Adequate watershed cover is critical on soils susceptible to wind erosion. Also, wind erosion on undisturbed rangeland soils is generally reduced by the presence of biological, physical, or chemical crusts on the surface (Chow and Watson 1997). Disturbance can break up those crusts and greatly increase susceptibility to wind erosion. Two widely used wind erosion models are available, the Wind Erosion Equation (WEQ) and the Wind Erosion Prediction System (WEPS), but both are applicable only to cropland. There are currently no models that predict wind erosion on rangeland. However, WEQ and WEPS may be applied to bare, devegetated rangeland sites, such as after a severe fire.



This is an example of naturally occurring rill erosion on a highly erodible soil.

Design Considerations for Erosion Monitoring and Assessment

The most basic consideration regarding erosion monitoring is to determine if it is actually needed. Is it required in a management plan either for quantifying a specific, anticipated impact or as an indicator of land health? Is it necessary to ensure compliance with a rule or regulation, such as water quality standards or required road construction practices? Can it provide a measure of the effectiveness of a planned management activity or mitigation? Will it provide a required performance measure, such as trend in upland condition? Will the monitoring answer the question that needs to be answered in the given timeframe? Does assessment indicate a potential erosion problem that needs to be monitored to determine if management objectives are being met?

Assessment is the process of estimating or judging the value or functional status of ecological processes in a location at a moment in time (Pellant et al. 2005). Monitoring is the orderly collection, analysis, and interpretation of resource data to evaluate progress toward meeting management objectives (Pellant et al. 2005).

The management objectives of any plan or project are the keys to its success. They articulate how issues will be resolved and how overall goals will be achieved. They represent a level of agreement among all the parties to the plan. They should be clear, measurable, and attainable. Consequently, the design of the monitoring plan should 1) flow smoothly from the objectives and 2) focus on selection of the best technique for determining if the actions taken to meet the objectives are succeeding (Elzinga et al. 1998; Herrick et al. 2005; Jackson et al. 1985a).

If erosion monitoring is being conducted over a large area, the next step is to stratify your landscape into monitoring units. These monitoring units should have similar management or land use characteristics and similar soil-landscape-ecological site characteristics. Next, you should try to predict the effects of current management on the monitoring units. Important considerations include legal requirements, resource use conflicts, threats to soil stability, and ecosystem drivers that could cause accelerated soil erosion (Jackson et al. 1985a). An on-the-ground assessment using methodology, such as those outlined in Technical Reference 1734-6 Interpreting Indicators of Rangeland Health, Version 4 (Pellant et al. 2005), may also be used to identify potential erosion problems. Based on risk of undesirable effects, you should determine which of the stratified units need to be monitored. Then select your monitoring indicators, such as cover or bare ground, or directly measure an indicator such as erosion. This step would not apply if you were monitoring the effectiveness of a specific erosion control structure.

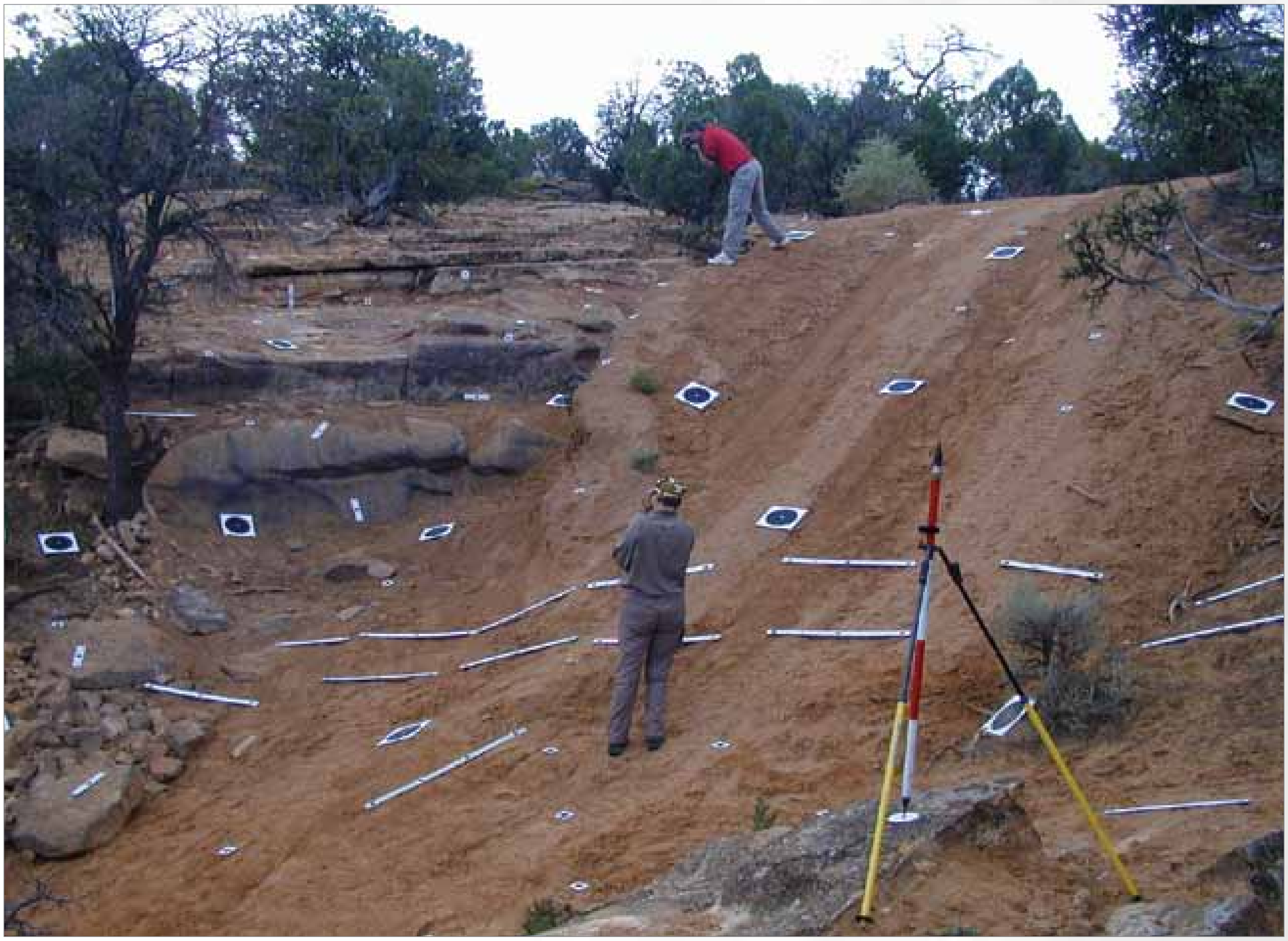
Based on how the data will be used, determine the number of monitoring plots, transects, or sites and the frequency of your monitoring. Determine how statistically valid the data needs to be. Factors that will influence statistical validity and reliability include the method used to determine monitoring site locations (random, stratified random, or subjective), biases of the monitoring method, adherence to data collection standards, data collection from controls or comparison sites, number of replicate sample sites, overall number of samples collected, and use of the appropriate statistical test (Herrick et al. 2005; Jackson et al. 1985a; Schreuder et al. 2004). Also answer the following questions. What are the resource values at stake? What legal requirements must be met? How many measurements are needed to detect change with a reasonable degree of certainty? You are then ready to select your specific monitoring locations.

Erosion monitoring should be conducted at a location most representative of a watershed or portion of a watershed, such as an allotment, forest management area, energy development area, or off-highway vehicle area. Key areas already selected for allotment monitoring or other monitoring may not be the best location for soil erosion monitoring. Erosion monitoring should be conducted as part of the overall monitoring strategy for a field office. The soil and vegetation types of the monitoring site need to be identified in order to help determine departure from natural erosion rates, resilience of the soil resource, and other factors. This is especially important if a comparison area that has not been impacted by past management or land use practices is not available or will not be monitored. The erosion plot or transect should be contained within one soil type and/or ecological site. The location of the monitoring site should be recorded by using a global positioning system (GPS) unit. It is also helpful to take digital photos of the monitoring plot or transect.

Most water erosion occurs as a result of extreme precipitation events (Poesen et al. 1996). Monitoring studies need to last long enough to capture these events. Thus, soil erosion monitoring and data collection should be conducted for at least 3 years in order to draw any general conclusions.

The actual method selected for monitoring should be based on the amount of accuracy and precision needed for the monitoring data, ability to detect a difference, method cost, time requirements for conducting the method, amount of time needed for monitoring, and availability of qualified personnel to conduct the monitoring, analyze the data, and report the results.

Monitoring data should be recorded carefully in the field to avoid data errors. If the field data set is recorded on paper, it should be transferred to a standard database to preserve a permanent electronic copy. Currently, the BLM does not have a standard agency database for erosion or other monitoring data, but a commercial off-the-shelf database or spreadsheet should be used to preserve the data. This allows data to be easily retrieved, analyzed, and shared with others. The analysis method should be part of the monitoring plan, widely accepted by the scientific community, and applicable to the monitoring goals. For example, if assessing impacts or monitoring a prescribed burn using cover data, you should select an erosion model, such as WEPP, that predicts erosion for specific storm years rather than one that predicts average annual erosion.



BLM geographer Neffra Matthews (bottom) and BLM physical scientist Tom Noble take a series of photos so they can use close-range photogrammetry methods to create three dimensional surface information to help quantify effects from rapidly increasing off-highway vehicle (OHV) use in the Dry Creek Extreme OHV Area.

Erosion Monitoring and Assessment Methods

Visual Indicators of Erosion

Background

The relative degree of erosion can be estimated by observing certain visual signs, such as pedestals, rills, litter movement, flow patterns, deposition, wind-scoured blowouts, and gully features. Visual indicators provide a qualitative assessment of erosion. Section 4180 of the BLM Manual directs the BLM to develop rangeland health standards in consultation with Resource Advisory Councils and evaluate the health of public lands. In addition, BLM Handbook H-4180-1 provides guidance stating that standards must conform to the four fundamentals of rangeland health, including watershed function. Indicators of watershed function generally include visual indicators of erosion.

Procedure

Along with Soil Surface Factors, visual indicators were commonly used to measure erosion in the 1970s and early 1980s as described in the Erosion Condition Classification System (Clark 1980). Some of these indicators are currently used as part of the rangeland health assessments and are described in Technical Reference 1734-6 Interpreting Indicators of Rangeland Health, Version 4 (Pellant et al. 2005). When rangeland health assessment is conducted using guidance from the technical reference, the ecological site for the assessment location is determined; the present status of erosion-based indicators is compared with the reference condition status of these indicators; and the departure differences are recorded on reference sheets (Pellant et al. 2005).

Advantages and Disadvantages

Major advantages of using visual indicators include 1) a relatively quick process, 2) many observations can be made during a field trip, and 3) potential erosion problems that require site-specific monitoring can be identified.

The major disadvantages of using visual indicators are that 1) this method is subjective, and many judgment-based decisions must be made, 2) there can be variation among ratings by different observers if adequate training is not provided, 3) the ratings can vary based on the timing of observations relative to when a major storm occurred, 4) the ecological site must be known, and a reference sheet is required, and 5) this technique needs to be used by knowledgeable, experienced personnel. Interpreting Indicators of Rangeland Health, Version 4 (Pellant et al. 2005) states that the qualitative protocol they describe is not to be used to monitor land or determine trend.

Data Analysis

Visual indicators of departure from reference conditions are recorded on the data sheets for the rangeland health assessments. Departures from reference ratings are recorded for each of the indicators, and a summary rating is recorded for soil and site stability, hydrologic function, and biotic integrity. Sites that indicate potential erosion problems should be red flagged so future quantitative monitoring can be conducted or so mitigating measures can be implemented to correct the problem.

Watershed Cover

Background

Watershed cover protects soil from the erosional forces that initiate soil loss. Each ecological site has its own potential cover that should be used as a reference to determine departure from the natural range of variability. Current ecological sites may not include plant cover information. In this case, the information may need to be collected from a reference site. Monitoring cover is needed to quantitatively determine the impact that land management activities and natural disturbances (such as wildfire and drought) have on watershed conditions. Changes in cover are sensitive to management actions but can be difficult to interpret due to the wide amplitude of natural variation created by annual climate fluctuations. For trend comparisons in herbaceous-dominated plant communities, basal cover is the most stable since it does not vary as much due to climatic fluctuations or current-year grazing (Cooperative Extension Service et al. 1999). However, canopy or foliar cover is more closely correlated to raindrop erosion.

Canopy cover is the percent of ground covered by a vertical projection of the outermost perimeter of the natural spread of plant foliage. Small openings within the canopy are included as part of canopy cover. Foliar cover is similar to canopy cover, but small openings within the canopy are not included. This is effectively the area that is protected from raindrops. Canopy gaps affect wind erosion by increasing wind velocity at the soil surface and rill erosion by increasing concentrated overland flow of runoff (Herrick et al. 2005). Thus, the canopy gap intercept method can provide useful information about soil erosion susceptibility that is not indicated by total cover measurements alone.

Procedure

Cover changes are most accurately monitored using permanent plots or transects that are periodically revisited. Cover can be quantitatively measured using the step-point method, line-point intercept method, line intercept method, gap intercept method, methods using the points on a frequency frame, photo plots, or other methods (Cooperative Extension Service et al. 1999; Herrick et al. 2005). The canopy gap intercept method provides an indication of the extent to which plant cover is aggregated or dispersed. Cover can also be estimated using techniques such as the Daubenmire method. Using a quadrat frame, such as with the Daubenmire method, to estimate cover is not recommended by some authors (Floyd and Anderson 1987; Kennedy and Addison 1987). Other authors believe it to be a reasonably accurate method of determining cover (Bonham et al. 2004; Daubenmire 1959; Hanley 1978; Stohlgren et al. 1998). Each of the other methods has advantages and disadvantages that should be taken into consideration. Cover can be expressed as ground cover, basal cover, canopy cover, or foliar cover, depending on the monitoring objective.

A laser point frame has been recently developed that can accurately measure cover (VanAmburg et al. 2005). It is constructed from aluminum alloy and has a T-bar, telescoping legs, and a main tube that contains 10 equally spaced lasers and electrical components. When the instrument is turned on, 1-millimeter diameter red laser dots, which are easily seen in sunlight, are projected directly downward, and the cover category is identified for each dot. Test results indicated a relatively high correlation (r+0.62-0.81) between cover data collected using the laser point frame and a magnetic (standard) point frame (VanAmburg et al. 2005). Material costs for the laser point frame were about $700, and development and construction costs were $926.

Advantages and Disadvantages

Advantages include the fact that quantitative measurement of cover is objective, repeatable, rapid, relatively simple to perform, and can be done simultaneously with rangeland condition and trend monitoring. Changes in cover can also be tied easily to livestock and wildlife management objectives. A study measuring shrub cover showed that 1) the line-point intercept method required about half the time in the field than the line intercept method and less time in the office, 2) the line intercept method provided better results than the line-point intercept method for species with low cover (3 percent or less), and 3) the two methods provided similar results and precision for species with higher cover (Heady et al. 1959). When estimating cover, the advantages of using techniques such as the Daubenmire method are that it is simple and rapid to use.

The disadvantage of measuring or estimating cover is that 1) it is an indirect indicator of erosion, 2) canopy and foliar cover are difficult to interpret due to the natural variation created by annual climate fluctuations, 3) monitoring needs to be done at a similar time of year, and 4) monitoring should be done during a rest period from livestock grazing. In addition, cover can be overestimated using step-point and frequency methods. The line intercept method is not well adapted for measuring cover on single stem species, dense grass, litter, or gravel with less than ½-inch diameter. The step-point method can be highly biased in vegetation that makes it difficult to pace in a straight line. The line point and line intercept methods take more time than the step-point method. The disadvantage of estimating cover using the Daubenmire frame is that it is not intended for plants greater than 1 meter in height, and if data are summarized using the midpoints for the cover classes, precision will be lowered over time. Ocular cover estimates using large plots are subject to observer bias and require extensive training and repeated comparisons with measured data and the results of other observers.

Data Analysis

The resource specialist can use cover data in several ways. One way is to compare the trend of cover data for the same plot from one monitoring cycle to the next. If canopy cover is included, the data would ideally be corrected for annual climate fluctuations. Methods to make these corrections are not currently available. Changes in basal cover may be more easily compared. Canopy or foliar cover does correlate better with raindrop erosion though. The climate data may also be compared to the cover of the reference condition for the same ecological site. To determine how much impact the change in cover has on water erosion, the cover data could be entered into an erosion model such as WEPP or RUSLE2. The other input factors for WEPP or RUSLE will need to be collected for the site. The U.S. Forest Service WEPP interface is the quickest and easiest version of the model to make erosion calculations. GeoWEPP is a geospatial interface that can be used to predict erosion on a watershed scale.

Remote Sensing Cover

Background

Remote sensing can be defined as broadly as "the acquisition of information about an object without being in physical contact with it" (Elachi and van Zyl 2006). A much more narrow definition is "the sensing of the Earth's surface from space by making use of the properties of electromagnetic waves emitted, reflected or diffracted by the sensed objects, for the purpose of improving natural resources management, land use and the protection of the environment" (United Nations 1986). Remote sensing, in the context used in this section of the technical note, includes any data collected remotely from the ground, aircraft, or satellites, including ground-based and aerial photographs and satellite imagery. Cover monitoring is well adapted to remote sensing frameworks at both a fine and coarse spatial scale and using various scales of imagery. Fine scale refers to small spatial extent, and coarse scale refers to broad spatial extent.

Procedure

Photography may be taken from the ground, specially-equipped airplanes, helicopters, balloons, tethered blimps, kites, or radio-controlled model planes. Stereoscopic ground-based and aerial photographs are routinely taken in black and white panchromatic, black and white infrared, color visible, color infrared, and multiband types. High resolution ground-based and aerial photos are appropriate for fine-scale cover monitoring. QuickBird and IKONOS images and other single band and multispectral imagery may also be used for fine-scale cover monitoring. Imagery should be of fine enough resolution to detect total cover changes as accurately as ground-based measurements. New advances in ground-based (Booth et al. 2004; Booth et al. 2005; Booth et al. 2006b; Booth et al. 2006) and low-altitude (Blumenthal et al. 2007; Booth and Cox 2006; Booth and Cox 2008; Booth and Tueller 2003; Seefeldt and Booth 2006; Sivanpillai and Booth 2008) remote sensing may give us the ability to accurately measure bare ground and perhaps other cover indicators. Resolution up to 1 millimeter has been obtained from low-altitude aerial imagery captured at a height of 100 meters (Sivanpillai and Booth 2008). Some ground-truthing may still be required though for low-altitude acquired imagery. In the past, costs for contracting image capture, processing, and classifying data have been relatively high, but they have recently been substantially reduced.

Many recent advances in technology have occurred. Booth and others (Blumenthal et al. 2007; Booth and Cox 2006; Booth and Cox 2008; Booth and Tueller 2003; Seefeldt and Booth 2006; Sivanpillai and Booth 2008) have done considerable testing using low-level flights with an ultralight plane to acquire imagery for cover change detection in Wyoming. Slaughter et al. (2008) are testing the use of unmanned aerial vehicles to acquire remotely sensed data for rangeland cover monitoring in New Mexico. Homer et al. (2008) have tested a predictive model to extrapolate QuickBird imagery training data to Landsat imagery in southwest Wyoming. Several of these projects have been conducted on BLM-administered lands and/or supported with BLM funding.

Multispectral imagery that is taken from a satellite at regular intervals and archived, such as Landsat, ASTER, and MODIS, is appropriate for coarse-scale cover monitoring. As an example, Robinove (1981) reported Landsat images to be effective in monitoring arid regions. These images would be appropriate for regional monitoring efforts. Each image covers a large area in a single view, and sampling could be done on a regional scale. Ground-truthing or training data using high-resolution imagery would be required for cover monitoring using multispectral imagery taken from a satellite. Contracting costs for processing and classifying multispectral data are moderate.

Some countries are much further advanced in the use of remote sensing for inventory and monitoring than the United States. Case in point, methods were developed in Australia to use Landsat TM imagery to estimate ground cover and identify trends in land condition, both spatially and temporally, in Queensland's rangelands (Taube et al. 2001).

Combining information from high- and low-altitude sensors appears to offer an optimal path for developing a practical system for cost-effective, data-based rangeland monitoring and management (Booth and Tueller 2003; Sivanpillai and Booth 2008).

Advantages and Disadvantages

The advantages of remote sensing are that it allows for extensive, unbiased, economical cover sampling; and the measurements, especially when done by computer image analysis, have the potential to reduce the human-judgment factor. Booth and Tueller (2003) proposed that data collection through remote sensing appears the most logical approach to acquiring appropriately distributed information over large areas in short time periods and on random sites far removed from easy ground access. Compared to ground-based cover monitoring, fewer people are required to do the monitoring, and besides cover, considerable additional inventory or monitoring data can be obtained from the images. When using satellite-based remote sensing images, the same image can be reacquired at regular intervals. The electronic images are also permanently available for additional analysis using different techniques or evaluating different features.

One disadvantage is that multispectral data is surrogate data. This presents spatial relationships and spectral reflectance properties rather than direct measurements of an indicator. Thus, ground-truthing is still needed with our current capabilities and for the foreseeable future. In addition, some vegetation types, such as fine-textured, annual grasses or forbs, do not lend themselves to accurate cover detection using remote sensing. Liability and safety are also of concern when acquiring remote sensing data from low-level flights of manned aircraft.

Data Analysis

Analysis of the raw, remotely sensed data is a major workload unless the process is automated. Fortunately, recent developments in automating the data analysis have greatly reduced the workload (Booth and Cox 2008). The process can now be automated to the point that the analysis selects the significant level of change of albedo (spectral reflectance) to be displayed (Booth and Cox 2008; Robinove 1981). Once this is complete, data analysis of the significance of cover data changes will be similar for both ground-based and remotely sensed data. The main difference will be that coarse-scale cover data could be used for regional analysis. As described previously in the data analysis section under watershed cover, erosion prediction models can be used to convert the cover data into erosion rates.

Silt Fence Catchments

Background

Silt fences have been used to control surface erosion from highway and other construction projects for decades. They allow water to pass through while trapping sediment. Silt fences can also be used as an easy-to-install, low-cost way to measure hillslope water erosion.

Procedure

Silt fences are placed in locations where they can collect erosion from a contributing area defined by natural or manmade features. Contributing areas should not exceed 21,000 square feet (Robichaud and Brown 2002). Dissmeyer (1982) recommends that the land slope be representative of the area being managed and not less than 3 percent. Silt fences are not designed to measure erosion rates in continuous flowing water channels, such as first-order streams.

The silt fence is installed at the base of the plots with suitable silt fence fabric and wooden or metal stakes to secure the material upright 18 to 30 inches above ground level. It is important to bury the bottom of the silt fence fabric below the ground surface to prevent runoff and sediment from escaping under the silt fence. Robichaud and Brown (2002) recommend sprinkling red chalk over the ground to define the boundary between the native ground surface and deposited sediment.

The silt fence is cleaned out periodically to obtain reliable measurements of erosion. Dissmeyer (1982) suggests using a flagged grid, an elevation bench mark, and surveying equipment to determine the volume of sediment trapped behind the silt fence. Silt fences will last up to 3 to 5 years. The mean trap efficiency of a properly installed silt fence has been measured at 93 percent the first year on a storm-by-storm basis and 92 percent the second year when only measured at the end of the runoff season (Robichaud et al. 2001).

Advantages and Disadvantages

The advantages of silt fences are 1) they are relatively economical compared to some methods (e.g., erosion plots), 2) they can be installed with a small field crew, and 3) they can be maintained at various time intervals. They also provide a good visual means of the amount of hillslope erosion to nontechnical stakeholders (Dissmeyer 1982).

The disadvantages are that 1) runoff and sediment may knock over or overtop the silt fence, 2) if not properly installed, runoff water may undercut the silt fence so that sediment is lost, 3) it is time consuming and arduous to dig out and measure the collected sediment, 4) the contributing area must be accurately measured, and 5) the silt fences only last up to 3 to 5 years. Livestock and wildlife can also knock over the silt fence. Lastly, if event sediment correlations are needed, the silt fences should be cleaned out after every major event.

Data Analysis

The volume or weight of sediment that is removed from the silt fence is measured periodically. This volume is divided by the acreage of the contributing area to obtain an erosion rate for the time period between cleanouts. The erosion rate can then be converted into tons/acre/year.

Bob Brown, hydrologist with the U.S. Department of Agriculture Forest Service, repairs a silt fence after the 2003 Myrtle Creek Fire on the Idaho Panhandle National Forest. The silt fences in this area were used to measure the effectiveness of straw mulch, hydromulch, and natural needle cast on reducing erosion after the fire.

Erosion Bridge

Background

The erosion bridge is an easy-to-use, inexpensive tool to estimate water or wind erosion in the field. The erosion bridge is a 4-foot aluminum masonry level placed on two fixed support pins that remain in the ground the length of the monitoring study. The distance to the soil surface is measured at 10 fixed points along each bridge by pins that are lowered to the ground surface. These measurements are used to calculate the average change in soil surface elevation.

Procedure

Sampling locations and orientation of the sampling bridge should be randomly selected within the area to be monitored (Blaney and Warrington 1983). Each sampling location should be accurately recorded with a GPS so it can be plotted as a data point. Two rebar are driven deep enough into the ground to remain stable and spaced so that the erosion bridge is level when mounted on the rebar. The modified masonry level is taken to the field and mounted on the rebar at each monitoring site. The level has 10 equally spaced holes drilled into the upper and lower flanges. A 2-foot metal pin is placed through each hole. The pins are lowered to the ground surface, and the distance is measured at each point (Blaney and Warrington 1983; Ranger and Frank 1978; Shakesby 1993). Measurements can be made to the nearest millimeter. A 1-millimeter reduction in soil depth represents about 5 tons per acre. Repeat measurements for each pin during each monitoring visit; these measurements indicate the

This erosion bridge is being used to determine the amount of wind erosion at a wildfire site in Idaho two years after the burn.

change in soil surface elevation and thus erosion or deposition. Sampling is repeated at desired time intervals to determine the erosion rate.

Advantages and Disadvantages

The advantages of the erosion bridge are that it is an inexpensive, rapid, and unbiased method for monitoring erosion. However, the plot location and orientation must be randomly selected to avoid bias.

The disadvantage of the erosion bridge is that the rebar can move if disturbed by humans, vehicles, or animals, or as a result of frost heave which renders the measurements meaningless. In addition, the pins are rather thin and somewhat flexible, so if they do not fall on the exact same spot, the measurement will not be accurate. The erosion bridge only works in shrub interspaces. Also, the area sampled and the number of sampling points is rather small, so numerous sampling plots would need to be established on a hillslope to ensure that an accurate representation of hillslope erosion is obtained. Ideally, samples should be taken at several points up and down the hillslope when determining water erosion.

Data Analysis

These data are used to calculate the average change in the soil surface elevation. This can then be converted into erosion rates. T-statistics can be used to calculate a confidence interval for the mean, compare a measured mean with a standard value, or compare the values of two measured means (Blaney and Warrington 1983).

Erosion Plots

Background

Erosion plots can be used as an accurate monitoring technique for estimating differences in annual runoff and soil erosion. Plots 50-feet long by 10-feet wide, collection tanks, and cumulative mechanical stage-height counters are used to construct the plots.

These erosion plots were used to estimate sediment production from water erosion events on mixed grass rangeland in eastern Montana.

The plots are replicated, and the pairing provides a control. The plots can be paired for grazed and ungrazed conditions, treated and untreated plots for restoration project monitoring, or other impact analysis.

Procedure

Jackson et al. (1985b) describe a procedure for construction and instrumentation of paired runoff and soil-loss monitoring plots. Plots 50-feet long by 10-feet wide are constructed in pairs to collect runoff and sediment. The side and upper border are wooden planks set into the soil and supported by surveyor stakes. The lower border is a standard metal rain gutter set into the soil with its upper edge at ground level. The rain gutter is placed at an angle to the slope with a slight drop and ensures movement of sediment through the gutter. A length of angled roof edging is placed above the gutter and attached so that it overhangs the gutter edge; this provides a stable runoff surface into the gutter.

The gutter collects water and sediment that is transported to a collection trough via a downspout. The collection tank is a 100- or 200-gallon oval stock watering trough. The water level in the tank is recorded by a mechanical float counter that will cumulatively measure increases in stage. Thus, evaporation losses will not affect the readings. The counter is read yearly, along with the measurement of the volume of sediment collected. Plots should be located in close proximity to each other to ensure that they have the same slope, aspect, soil, precipitation, and ecological site characteristics.

Advantages and Disadvantages

The advantages of using erosion plots are 1) long-term runoff and erosion rates are measured, 2) these plots correspond to the standard 0.01 acre plot unit used to develop soil-loss parameters for the Universal Soil Loss Equation, 3) they are accurate at the plot scale if no losses occur from the plot or collection tank, 4) replication plots can be established, 5) control plots can be established, and 6) data can be compared using statistical techniques and analyzed using RUSLE, WEPP, or other common erosion models. If no losses occur from the plot or collection tank, erosion plots can also be used to validate erosion prediction models, such as WEPP and RUSLE2.

The disadvantages of using erosion plots are 1) equipment failures, including loss of runoff and sediment along the plot borders, overtopping of the collection tank, and potential livestock or wildlife damage to the plots, 2) the chance of improper site selection or plot installation, 3) difficulty in finding duplicate site conditions for the erosion plots, 4) potential rodents burrowing under the plot borders can result in loss of runoff and sediment, 5) wind erosion is not measured by this technique, 6) relatively high installation and maintenance costs, and 7) the effect of the plot borders on erosion processes. Erosion measured from small plots can underestimate or overestimate the erosion occurring on a hillslope scale (Boix-Fayos et al. 2006; Taube et al. 2001). A couple factors could cause underestimates. For one, the upper plot border could reduce overland flow within the plot. Also, erodible material could be exhausted within the plot. Overestimates can result from the fact that the disturbances along the plot border may increase detachable material, and the upper plot border reduces soil deposition within the plot (Boix-Fayos et al. 2006).

Data Analysis

If only one plot is established, regression can be used to quantify change in erosion and runoff over time. However, no significant trend over time can be established. If two or more plots are established, but a control is not established, probability statements can be established to a change over time, and confidence limits can be created for sediment yield or runoff for any given year or group of years. However, change over time cannot be related to management actions. If two or more plots are established for both the control and management-impacted areas, statistical analysis can be done for probability, and confidence and management implications can be determined (Jackson et al. 1985b).

Close-Range Photogrammetry

Background

Close-range photogrammetry is an excellent method for capturing detailed information about erosion on plots ranging in scale from 1 square meter up to an entire hillslope. The software creates a digital terrain model with grid spacings of 1–2 millimeters and can detect vertical elevation changes with submillimeter accuracy on smaller plots. This methodology is especially effective for monitoring erosion on areas that will remain devoid of vegetation, such as roads, off-highway vehicle trails, and construction sites. This method is also appropriate for measuring sediment that accumulates in a sediment trap that is designed to monitor erosion in a catchment basin.

Procedure

Close-range—also referred to as terrestrial or ground-based—photogrammetry is defined as that having a distance of less than 300 meters from camera to object (Matthews et al. 2006). A calibrated camera is used to capture x, y, z coordinate data in a series of oblique orientation, overlapping photographs that are taken of the subject area with circular reference targets, circular coded targets, and an object of known dimension placed within the target area (Matthews 2008; Ypsilantis et al. 2007). One or more permanent, fixed points is also needed as a reference for elevation. For larger size plots, three or four reference elevation points are needed. The reference points consist of bedrock or rebar driven deep enough in the ground to remain stable, with the top slightly below the ground surface so that they will not be disturbed and do not present hazards to recreational users. The rebar location is recorded with a GPS, and a GPS unit and metal detector are used to relocate them for subsequent plot measurement. This is an emerging technique with image processing expertise that is currently available from the BLM National Operations Center (NOC). Photos can be taken by field personnel and processed by the NOC's photogrammetry personnel.

Laptop computers with PhotoModeler® or 3DM Analyst software (ADAM Technology, Australia) can be used to create digital terrain models that consist of a closely spaced grid with thousands of x, y, z data points (Matthews 2008; Ypsilantis et al. 2007). Using the photos taken of the monitoring plot or hillslope, the software creates a mosaic based on sophisticated automated recognition of coded targets and similar ground features between photos. Initial photo processing can be done in the field within a few minutes of downloading the digital photo images. The three-dimensional digital terrain datasets are then analyzed in ArcGIS using ArcMap and ArcScene. A tin surface is created and converted to a grid, and a hillshade is generated from the grid for each dataset (Matthews 2008; Ypsilantis et al. 2007). To determine changes in elevation of soil surface features, the surface grids created from initial sampling data are compared to data taken during a later sampling period.

Dennis Murphy, BLM soil scientist (retired), captures a series of overlapping images to create a digital terrain model of the Falcon Road Open Off-Highway Vehicle Area. Close-range photogrammetry can be used to determine changes in soil surface features by comparing the surface grids created from initial sampling data to data from later sampling periods.

Advantages and Disadvantages

The advantages of the methodology are 1) erosion can be directly measured to a high level of accuracy for a variety of plot sizes, from 1 square meter up to an entire hillslope, in a quick, efficient manner, 2) the cost of field equipment is low, 3) thousands of data points are collected for each plot, 4) the ability to drive rebar control points below the ground surface eliminates risk of disturbance and risk of safety hazard for recreation vehicle users, 5) detailed maps of the spatial pattern of soil erosion are produced for the entire hillslope, and 6) the photos and derived data sets are permanently stored electronically. This methodology could also be used to validate erosion models.

The disadvantages are 1) the processing software needed for larger size plots is currently expensive, 2) vegetation can obscure the ground surface and reduce the ability to make measurements on that portion of the site, and 3) there are few current sources of the expertise to conduct this monitoring. Another disadvantage is that any movement of litter, rocks, or other objects on the ground surface will be interpreted by the software as a soil loss and gain. This can bias the results of the analysis unless those data points are removed from the data set. Fortunately, erroneous data points can be removed from the data set during processing.

Data Analysis

ArcGIS software is used to determine cut and fill and surface subtractions for the surface grids within the monitoring plots or hillslope. The net soil loss or gain volume is divided by the area to determine loss or gain per area or tons per acre of erosion. Close-range photogrammetry can be used to determine soil loss and gain rates to subcentimeter accuracy for hillslopes and submillimeter accuracy for 1 square meter plots. The ADAM Technology 3DM software quickly and efficiently processes the digital photogrammetry data for a project. The close-range photogrammetry methodology has promising potential application for directly measuring erosion caused by a variety of soil disturbing activities.

Cesium-137

Background

Cesium-137 has been widely used over the past few decades to monitor soil erosion. Cesium-137 is an artificial radionuclide with a half-life of approximately 30 years. It was globally distributed by the deposition (mostly by rainfall) of fallout from atmospheric nuclear weapons tests in the mid-1950s through the mid-1960s (Cambray et al. 1989; Carter and Moghissi 1977; Playford et al. 1993; Ritchie et al. 2003). Once cesium-137 reached the soil surface, it strongly and quickly adsorbed onto the exchange sites of the soil particles and was essentially nonexchangeable in most environments (Cremers et al. 1988; Ritchie et al. 2003; Tamura 1964). Physical processes of water and wind erosion are usually the dominant factors moving cesium-137-tagged soil particles between and within landscapes (Ritchie and McCarthy 2003; Ritchie and McHenry 1990).

Procedure

Soil core samples are collected from the study area and from undisturbed reference sites that are assumed to have little erosion or deposition. Cored samples can be sliced to show the depth distribution of cesium-137. Samples are air-dried or ovendried and sieved through a 2-millimeter mesh. Subsamples are packed into Marinelli beakers or small plastic pots and analyzed with a gamma-ray spectrophotometer. Identification of cesium-137 loss and gain for each sampled location is made by comparison with the measurement from the reference sites. Estimates of soil erosion/deposition for each sample site can be made using various models, such as the cesium-137 profile distribution model (Walling and He 1999; Walling and He 2001).

Advantages and Disadvantages

The main advantage of using cesium-137 for erosion monitoring is that it is suitable for long-term erosion studies at a watershed or landscape scale (Bernard and Laverdiere 2001; Ritchie and McHenry 1990). Variations in erosion and deposition over a hillslope or within a catchment are possible. Cesium-137 also has potential for the study of source areas of sediment and sediment routing on hillslopes (Loughran 1989). Other advantages are that cesium-137 data can be used to estimate wind erosion when applied to a large area (Sac et al. 2008), only a single sampling trip to the field is required, and cesium-137 allows a sampling strategy to provide any spatial resolution required (Ritchie 2001).

The main disadvantage is that cesium-137 is not suitable for relatively short-term monitoring of the effect of management actions on erosion rates, which is the information needed by land management agencies, such as the BLM. Also, laboratory analysis costs for numerous samples would be potentially expensive.

Data Analysis

Estimates of soil erosion or deposition for each sample site can be made by using various models, such as the cesium-137 profile distribution model (Walling and He 1999; Walling and He 2001). Indepth descriptions of other models used for estimating soil loss or deposition are provided by Walling and He (1997) and Walling and Quine (1990).

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Appendix 1: Erosion Monitoring Methods Comparison Table

METHOD	Direct measurement or indirect indicator	Spatial scale	Relative cost and rapidity	Relative accuracy and reliability	Applicable to water and wind erosion	Appropriate monitoring or assessment application
visual indicators of erosion	indirect indicator	local, regional, and national	inexpensive and rapid	qualitative, can vary between observers	both	land health assessment, erosion over short- and long-term time periods indicated
watershed cover	indirect indicator	local	inexpensive, rapidity depends upon specific method used but can be time consuming	quantitative, estimated cover can vary between observers, climate impacts canopy cover	both	condition and trend monitoring, effectiveness and postfire monitoring, indicates current susceptibility to erosion
remote sensing cover	indirect indicator	local and regional	inexpensive and rapid	Accurate except for fine-textured grasses and forbs, reliable	both	condition and trend monitoring, effectiveness and postfire monitoring, indicates current susceptibility to erosion
silt fence catchments	direct measurement	local	moderate expense, time consuming to clean out	accurate if properly constructed and maintained	water only	effectiveness and postfire monitoring
erosion bridge	direct measurement	local	inexpensive and rapid	accurate if undisturbed, reliability depends upon number of samples taken	both	effectiveness and postfire monitoring
erosion plots	direct measurement	local	moderately expensive and time consuming to install and maintain	accurate and reliable if properly installed and maintained	water only	effectiveness and postfire monitoring, long-term studies
close-range photogrammetry	direct measurement	local	software expensive, very rapid	very accurate and reliable	both	effectiveness and postfire monitoring, long-term studies
cesium-137	direct measurement	local and regional	lab analysis expensive if numerous samples collected, rapid	accurate and reliable	both	long-term studies evaluating erosion during past 40+ years